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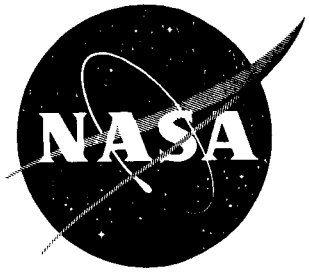

TECHNICAL NOTE

D-259

ROLLING-CONTACT FATIGUE LIFE OF A CRYSTALLIZED GLASS CERAMIC

By Thomas L. Carter and Erwin V. Zaretsky

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

The five ball fatigue tester was used to evaluate a crystallized glass ceramic (Pyroceram 9608), a potential high-temperature bearing material, with respect to rolling-contact fatigue life. Controlled variables included ball loading (contact stress), contact angle, ambient temperature, test lubricant, and specimen fabricator. These tests indicated that the crystallized glass ceramic may be useful in low-load, short-duration applications where an operating temperature above the limits of steels is the paramount design consideration.

Rolling-contact fatigue failure spalls similar to those observed for bearing steel balls were produced. Failures were localized in area and limited in depth of spalling. The room-temperature load carrying capacity was found to be approximately one-fifteenth that of a group of AISI M-1 bearing steel balls. Tests at maximum theoretical (Hertz) compressive stresses of 265,000, 295,000, and 330,000 psi showed fatigue life of the ceramic varied inversely with approximately the 11th to 13th power of stress.

The rate of failure spall development was much slower than that which is normal for steel balls. An intentional overrun for a period several times that which produced the initial failure spalling did not produce a general breakdown of the test surface. The scatter between short- and long-lived specimens was much lower for the crystallized glass ceramic than is normal for bearing steels. Since the ceramic does not have appreciable foreign matter comparable to nonmetallic inclusions in steel, this low scatter indicates that the degree of structural homogeneity may be an important factor in life scatter of bearing materials.

Variation in contact angle, which produces variations in relative sliding of the contacting surfaces, did not produce any significant differences in fatigue life of specimens run at the same contact load (Hertz stress). The fatigue life at 700° F was approximately one-third of that observed at room temperature. This may not indicate a thermal effect in

the material itself. Thermal effects on the test lubricant over this temperature range could produce this difference in life. Differences in life results with two different lubricants, a paraffinic mineral oil and a sebacate diester, correlate well with effects of lubricant viscosity and base stock previously observed with steel balls.

INTRODUCTION

Problems with mechanical strength, dimensional stability, and corrosion resistance preclude the use of metallic alloys for rolling-contact bearings at ambient temperatures much above 1000° F. Hot hardness, an important property of rolling-contact bearing materials, rapidly falls below acceptable values in this temperature range (ref. 1). To meet the increasing need for bearing applications at temperatures above the limits of alloy steels, ceramics are being considered as bearing element materials.

For applications in the temperature range extending several hundred degrees Fahrenheit above the limits of metallic alloys, crystallized glass ceramics offer promise. While they do not have the high strength and ductility of alloy steels, crystallized glass ceramics retain their strength, hot hardness, and corrosion resistance through higher temperature ranges. Very low thermal expansion coefficients permit control of bearing clearances over a wide range from room to operating temperature. Quality control is facilitated by the fact that glass base ceramics can be formed in the plastic state and this material, which is transparent before crystallization, can be visually inspected. These desirable properties make crystallized glass ceramics a promising material for rolling-contact bearing elements in applications where more conventional metallic alloys encounter excessive temperature-induced deterioration.

An important consideration in very high temperature bearing application design is lubrication and wear. Adequate lubricants have not been developed for temperatures in the range where the properties of crystallized glass ceramics make their use advantageous. Preliminary unlubricated tests showed that severe wear precluded runs long enough to produce fatigue failure. This indicates the necessity for some form of lubrication in a study of the fatigue life of Pyroceram. Very high temperature bearing development may depend upon the availability of adequate lubricants as well as materials. Solid and reactive gas lubricants show promise of meeting this need (ref. 2).

An evaluation of the rolling-contact fatigue life of a crystallized glass ceramic was undertaken in anticipation of lubricant developments which would make very high temperature bearing operation feasible. Test temperatures were of necessity limited by presently available lubricants.

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Since no published data are available on rolling-contact fatigue of ceramic materials, it was felt that a program at limited test temperatures would produce valuable information.

The crystallized glass ceramic material receiving widest attention in the bearing industry is Pyroceram 9608. Of the several formulations available it possesses the most desirable mechanical properties. Pyroceram is a glass-base substance which, through addition of selected nucleating agents and proper heat treatment, is structurally transformed into a semicrystalline substance (ref. 3). The crystalline phase, approximately 50 percent, is contained in a glassy matrix. The action of the crystals as stress distributors at the point of crack propagation produces the improvement in mechanical properties which is the basic advancement of crystallized glass ceramics over high-strength glasses.

One-half-inch ball test specimens of Pyroceram 9608 were run in the five ball fatigue tester against AISI M-1 support balls at a rotative speed of 2430 revolutions per minute. Ball loading produced maximum theoretical (Hertz) compressive stresses in the range 265,000 to 330,000 psi. Controlled variables included contact stress, contact angle, temperature, lubricant base stock, and production lot. The object of the research reported herein was to evaluate the rolling-contact fatigue life of crystallized glass ceramic (Pyroceram 9608) bearing balls and to show the effect of several environmental variables.

APPARATUS

Test Rig

The five ball fatigue tester (fig. 1(a)) used in this investigation is basically a modified bench-type drill press consisting of test section, special drive spindle, lever loading system, and lower support housing incorporating a heater to facilitate high-temperature testing. The test section consists of a driven test ball pyramided upon four lower balls positioned by a separator and free to rotate in an angular contact raceway. By varying the pitch diameter of the four lower balls, bearing contact angle θ (fig. 1(b)) may be controlled. The contact angle θ is the angle between the contact axis and the plane of lower ball rotation. For every revolution the spindle makes, the test specimen is stressed three times. Analysis of this is given in appendix A.

Specimen loading and drive are supplied through the special spindle that is notched at its lower end to fit the tongue cut on the driven test ball. Loading was accomplished by dead weights acting on the spindle through a load arm. Contact load was a function of this load and the contact angle. Choice of test specimen rotative speed is provided through

step pulleys driven by an electric motor. The raceway, which contains the freely rotating lower balls, is held by a housing containing eight cartridge heaters. The entire housing and the test specimen assembly are surrounded by insulation to permit efficient high-temperature operation and low ambient temperature gradients.

Two methods of supporting and alining the bearing housing assembly were available. In the method used to test the steel balls the housing and its surrounding insulation are supported by rods held in flexible rubber mounts. Positioning of the rods and rubber mounts provides for alinement of the raceway and four lower balls with the upper test ball and drive shaft. Minor misalinements are absorbed by the flexible rubber mounts. Vertical oscillations of the drive shaft created by rig vibration are absorbed by the rubber mounts. Such vibrations, if not dampened, will increase the stress level of the ball specimen through deflection of the specimen and thus influence fatigue life results.

An alternative method of housing support incorporates an air bearing (fig. 1(c)). Horizontal alinement was provided by the essentially frictionless air pad. Test specimen temperature in the air-bearing modification was maintained by electrical resistance elements heating the ambient air. This latter method of housing support was used in the crystallized glass ceramic investigations because friction torque measurements were desired and because more precise horizontal alinement was considered desirable with the brittle material.

Instrumentation

Instrumentation systems providing for speed measurement, temperature measurement and control, and failure detection and shutdown make long-term unmonitored operation possible.

A magnetic pickup feeding an electronic counter provides for precise measurement of the test ball rotative speed. This speed is used to convert total test time into stress cycles.

A thermocouple in contact with the raceway is linked to an automatic control for heater power. Temperature calibrations show that the control temperature is within 1 percent of the test specimen surface temperature. With the air-bearing support system, friction torque is measured with a calibrated strain gage.

Operating vibration is sensed by a velocity type vibration pickup and fed into a vibration meter where a filter removes low-frequency signals produced by normal rig operation. Higher frequencies which include those characteristic of failed specimens are automatically compared with a predetermined shutdown level. An increase in vibration to

an amplitude greater than the predetermined level results in shutdown of the apparatus and all instrumentation.

Test Specimens

Two groups of test specimens, identified as A and B, were procured from two different vendors as a check on performance reproducibility between production lots. Both specimen groups were formulated, cast into rough blanks and heat-treated by the same concern. The rough blanks for both groups are believed to have originated in the same production run. These rough, 3/4-inch-diameter blanks were then finished by two different grinding techniques to 1/2-inch-diameter balls by the two vendors.

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Lubrication System

The test specimen was lubricated by introducing droplets of fluid lubricant into an airstream directed at the test specimen. Lubricant flow rate was controlled by adjusting the pressure upstream of a long capillary tube. The pressure drop through the capillary was sufficient to give excellent control of the flow for small flow rates.

Two lubricants were used in conducting the rolling-contact fatigue tests. Most room-temperature tests were conducted with a synthetic diester, having a di-2-ethyl hexyl sebacate base, which met the MIL-L-7808C specification. It had a kinematic viscosity of 14 centistokes at 100° F. The second lubricant was a highly purified paraffinic mineral oil (Pennsylvania State University Petroleum Refining Laboratory MLO 7341) having a 100° F kinematic viscosity of 107 centistokes. At the high test temperature (700° F) this fluid was boiling, but the kinematic viscosity of the liquid phase as measured by the petroleum refining laboratory was approximately 1.1 centistokes. Hereafter these lubricants will be referred to as the diester and the mineral oil.

PROCEDURE

During storage, support balls, separators, and races were protected by a corrosion-resistant oil film. AISI M-1 support balls were grouped in sets of four having diameters matching within 10 millionths of an inch to ensure even loading of the test specimen at all four contact points. Prior to use and inspection all parts mentioned were flushed and scrubbed with absolute ethyl alcohol and dried with clean cheesecloth. Care was taken to prevent scratching of the Pyroceram test specimen and support balls. The Pyroceram specimens were kept clean and dry during storage. Before a test, the balls were measured and examined for

imperfections at a magnification of 60. Before a test was begun the Pyroceram ball and the support balls were coated with the test lubricant.

After completion of a test all the support balls were examined visually for imperfections. All four support balls were replaced if a defect such as a fatigue spall or mechanical damage was found in any one of them.

In assembly of the rig, the housing assembly (fig. 1(c)) was positioned normal to and concentric with the shaft by the essentially frictionless air-bearing pad. Air-bearing pressure was checked to ensure adequate support. The test specimen was then placed in the drive shaft and positioned on the support balls; care was taken to prevent any damage to the ball specimen. The load arm was put in place and the load applied. The rig was then immediately brought up to operating speed. When a high-temperature test was to be made, the specimen and housing were brought up to test temperature before the test was begun.

Time, speed, temperature, and oil flow were monitored and recorded at each reading. Periodic checks to observe failure progression were accomplished by shutting down the rig and examining the specimen for incipient cracking or a failure. If no fatigue spall was observed, the test was resumed until a failure occurred. A test ball was considered failed when a spall had developed across the entire track width.

The stress developed in the contact area under a particular load was calculated by using the modified Hertz formula given in reference 4.

Total running time for each specimen was recorded and converted into total stress cycles. Fatigue life data were plotted on Weibull paper, which has the log log of the reciprocal of the portion of the sample surviving as an ordinate and the log of the stress cycles to failure as an abscissa. From this plot the number of stress cycles necessary to fail any given portion of a specimen group may be determined.

RESULTS AND DISCUSSION

Preliminary Tests

A preliminary test of unlubricated Pyroceram against AISI M-1 support balls produced separator seizure, severe wear, and high friction torque. Figure 2 shows the severe wear of a lightly loaded ball (265,000 psi maximum compressive stress) after 10 minutes of running (70,000 stress cycles) at room temperature. Because of this experience further testing without some form of lubrication was not considered feasible. For this reason all further tests were conducted with fluid lubricant present.

Since no rolling-contact fatigue data were available on crystallized glass ceramic materials, a step load test was conducted to establish the general load carrying capacity of this material. Successive 30-minute periods at increased loading on the same test specimen produced a failure after 4 minutes of running time at a maximum theoretical (Hertz) compressive stress of 340,000 psi (fig. 3). This result indicated limited life at higher stress, and therefore all subsequent testing was conducted at lower stress levels.

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Failure Appearance

Figures 4(a) and (b) compare a before-test Pyroceram 9608 specimen with an after-test specimen. Their relation to the lower support balls and separator is shown. The upper test ball is canted to show the running track area. In figure 4(b) the limited extent of the failure spall relative to the total ball surface area can be observed. The crystallized glass ceramic produced rolling-contact fatigue failure spalls similar to those observed with bearing steels. Figures 5(a) and (b) show fatigue failure spalls for Pyroceram 9608 and AISI M-1, respectively. Spalls from both materials were localized in area and limited in depth of penetration. The surface crack pattern associated with the spall formation is similar for both materials.

A contrast between Pyroceram 9608 and bearing steels was observed in the rate of progression from incipient failure to a spall large enough to produce deleterious effects on performance such as increased vibration and torque. Fatigue failures in steel bearing elements usually propagate rapidly to a general spalling once the initial surface spall appears. For fatigue spalls of AISI M-1 balls, the propagation time was a fraction of 1 percent of the total fatigue life. Pyroceram 9608 balls showed a much slower rate of spall propagation than that of bearing steels. Figure 5(c) shows a failure spall which has developed in 1.8 million stress cycles. Figure 5(a) shows the fully developed fatigue spall (100 percent of track width) at 2.4 million stress cycles, and figure 5(d) shows the failure appearance after an intentional overrun to 9.2 million stress cycles. This slow rate of failure propagation was not anticipated for a very hard, brittle material such as crystalline glass ceramic. It suggests that the material may be resistant to crack propagation if the high rates of loading and predominantly tensile stress associated with fracture tests are avoided. In rolling contact of spherical specimens the principal stresses are in compression, and severe localized overstress due to nonuniform loading is avoided.

Steels and crystallized glass ceramics have some structural features in common which may account for the similarity of fatigue failure appearance. Figure 6(a) is an electron photomicrograph of Pyroceram 9608 away from the surface of the ball specimen. The predominant feature which dis-

tinguishes this material from glass is the presence of a crystalline phase consisting of randomly oriented rhombohedrons distributed in an amorphous matrix. The theories advanced for fatigue of steels are usually associated with the existence of a crystal structure. Thus, it is possible for crystallized glasses to behave similarly to steels when subjected to cyclical stressing. Furthermore, the crystals can act as a barrier to the crack propagation generally associated with brittle fracture across the entire section of a completely glass material. In none of the 61 Pyroceram specimens tested in this investigation was a general fracture failure observed.

Figure 6(b) shows structural changes in the subsurface zone of resolved shear stress in Pyroceram 9608. These structural changes bear superficial resemblance to those commonly observed in steel specimens in that the matrix damage tends to aline itself with the 45° plane of maximum shear stress. However, the existance of a glassy phase and the much finer crystal size of Pyroceram preclude more specific comparisons with matrix damage of steel specimens. The structural changes in Pyroceram were less localized than those usually observed in steel specimens.

Rolling-Contact Fatigue Life

Figures 7(a) and (b) are Weibull plots of rolling-contact fatigue life for 1/2-inch Pyroceram 9608 ball specimens tested at three stress levels. These specimens were tested at a 40° contact angle in the five ball fatigue tester at room temperature using the diester lubricant. Two groups of specimens (lots A and B), both from the same formulation and heat treatment but from different finishers, were tested to observe consistency of results from different sources of supply. Maximum theoretical (Hertz) compressive test stress and the 10-percent fatigue lives in stress cycles are shown in the following table:

Specimen lot	10-Percent fatigue life, stress cycles		
	Test stress, 265,000 psi	Test stress, 295,000 psi	Test stress, 330,000 psi
A	2,000,000	350,000	94,000
B	3,000,000	-------	300,000

Effect of Contact Stress

Figure 7 shows a decrease in rolling-contact fatigue life with increasing contact stress. Figures 8(a) and (b) are plots of the log of stress against the log of 10- and 50-percent fatigue lives for specimen lots A and B, respectively. These plots show fatigue life varying inversely with the 10.5 to 13.8 power of stress. These values, when compared with the inverse 9th to 10th power relation normally accepted by the bearing industry as representative of steels, show that Pyroceram 9608 is slightly more sensitive to stress than are steels.

As a compensating factor for this apparent higher sensitivity to contact stress, the low elastic modulus (12.5×10^6 psi) of Pyroceram 9608 allows greater elastic deformation of the contacting bodies; hence, the stress produced in Pyroceram 9608 is lower than that in steel at the same ball loading. This relation takes the form $S = K\left(\frac{y_a y_b}{y_a + y_b}\right)^{2/3}$, where y_a and y_b are the elastic moduli of the two contacting bodies and K is a factor dependent upon specimen geometry and load. A derivation is given in appendix B. The following table illustrates this point:

	y_a	y_b	$\frac{S_{max}/K}{\left(\frac{y_a y_b}{y_a + y_b}\right)^{2/3}}$	Ratio to steel on steel
Steel on steel	30×10^6	30×10^6	6.1×10^4	1.0
Steel on Pyroceram 9608	30×10^6	12.5×10^6	4.3×10^4	.71
Pyroceram 9608 on Pyroceram 9608	12.5×10^6	12.5×10^6	3.4×10^4	.56

Comparison of Ceramic Life with Tool Steel Life

Figure 9 is a Weibull plot of rolling-contact fatigue life of a group of 1/2-inch AISI M-1 tool steel balls run at a 40° contact angle in the five ball fatigue tester at room temperature using the diester lubricant. Thus, all test conditions are the same as those used in testing Pyroceram balls (fig. 7) except contact stress (800,000 psi maximum), which was of necessity much higher in order to fatigue the higher load capacity tool steel. Ten-percent failure life was 5,500,000 stress cycles.

Figures 7 and 9 may be used to compare the relative fatigue lives of Pyroceram and steel. Pyroceram 9608 (fig. 7) has much lower life than AISI M-1 (fig. 9) but, since the test stress was much higher for steel, the two materials cannot be compared directly. When materials are tested at different stress levels, direct comparisons of fatigue lives can be made only by adjusting one of the lives using the proper stress-life relation for that material, or by making a comparison on the basis of load capacity. Load capacity, contact load, and life are related by the equation

$$C = P \sqrt[n]{L_N}$$

where

C load capacity or contact load in pounds which will produce failure of 10 percent of test specimens in 1 million stress cycles

P actual contact load in pounds

n exponent relating load and life, determined experimentally

L_N actual 10-percent failure life in millions of stress cycles

For steels, n is usually taken as 3 (based on a stress-life exponent of 9, since stress varies as the 1/3 power of load). For Pyroceram, as determined in this investigation, n is approximately 3.9. The values of capacity listed in the following table were calculated using these values of P and L_N:

Material	n	Stress	P	L_N	C
AISI M-1	3	800,000	173	5.5	305
Pyroceram 9608					
Lot A	3.9	265,000	17.1	2.0	20.4
Lot A	3.9	295,000	23.8	.35	18.1
Lot A	3.9	330,000	33.3	.095	18.2
Lot B	3.9	265,000	17.1	3.0	22.7
Lot B	3.9	330,000	33.3	.30	24.4
Average					20.8

Based on these computations a load of 21 pounds would fail 10 percent of the Pyroceram 9608 specimens in 10^6 stress cycles, while a load of 305 pounds would be required to produce equivalent results with AISI M-1. Thus, the Pyroceram 9608 test balls of figure 7 have approximately one-fifteenth the theoretical room-temperature load capacity of the AISI M-1 test balls of figure 8.

Effect of Contact Angle

Figure 10 shows a Weibull plot for a group of specimen lot A balls run at a 10° contact angle in the five ball fatigue tester at 330,000-psi contact stress at room temperature with the diester lubricant. Ten-percent fatigue failure life was 120,000 stress cycles. For comparative purposes the ball group from figure 7(a) run at a 40° contact angle, but otherwise identical conditions, is shown as the dashed line in figure 10.

The degree of relative sliding between the two contacting surfaces $\omega_1 \sin \theta$ created by the twisting motion of one on the other changes as the angle of contact of one on the other changes. Figure 1(b) is a diagrammatic representation of this relation in the five ball tester. As the contact angle θ is increased, the relative spin velocity of the contacting surfaces is increased. Figure 10 shows that only a slight decrease in life is produced at the higher relative spin velocity (40° contact angle) compared with the lower relative spin velocity (10° contact angle) at the same contact load and stress. This insensitivity of Pyroceram 9608 to contact angle suggests the possibility of designing thrust bearings with higher contact angles than those normally used for steel bearings. Since contact loads vary inversely with the sine of the contact angle, this modification would improve the load carrying capacity of the bearing assembly.

Effect of Ambient Temperature

Figure 11 shows Weibull plots for two groups of balls from specimen lot A run at a 40° contact angle in the fatigue tester at 330,000-psi contact stress with the mineral oil lubricant at room temperature and at 700° F. Figure 4(c) shows a ball specimen after a 700° F test. Ten-percent failure lives of 470,000 and 123,000 stress cycles, respectively, were produced at these test temperatures.

Figure 11 shows a substantial reduction in fatigue life at 700° F from that observed at room temperature. Although actual data are not available, Pyroceram 9608, which has a softening temperature of 2282° F (ref. 5), should not experience an appreciable loss in strength at 700° F. On the other hand, the test lubricant experiences important changes in

properties between room temperature and 700° F. Its viscosity is reduced from 107 centistokes at 100° F to 1.1 centistokes at 700° F. Based upon the relation between life and viscosity established with AISI M-1 tool steel in reference 6, a reduction in life of about $3\frac{1}{3}$ to 1 would be expected because of lubricant viscosity effects alone. The actual reduction in life between the two test temperatures observed in figure 11 was 3.8 and 2.8 to 1 for the 10- and 50-percent failure lives, respectively. Thus the observed loss in fatigue life at the higher temperature could be accounted for by changes in lubricant properties, and a deterioration of the Pyroceram material itself did not necessarily occur. With proper lubrication, Pyroceram 9608 may be useful in the temperature range above 1000° F where alloy steels soften.

Effects of Lubricant Viscosity and Base Stock

The room-temperature results reported in figure 11 were obtained with balls from the same specimen lot (A) and under the same test conditions as the 330,000-psi tests reported in figure 7 with the exception of the test lubricant. The tests shown in figure 7 were run with the diester lubricant, whereas the figure 11 tests were run with a mineral oil. The higher viscosity mineral oil lubricant produced much higher life than that produced with the diester. References 6 and 7 state that life increases with higher lubricant viscosity, and references 7 and 8 state that mineral oils produce better life than diester oils. The following table is a comparison of actual 10-percent life results for Pyroceram 9608 with theoretical life ratios obtained for steels in references 6 to 8:

Lubricant	Viscosity at 100° F, centistokes	Theoretical life ratios due to differences in -			Actual life, stress cycles
		(a) Viscosity (refs. 6 and 7)	(b) Lubricant base stock (refs. 7 and 8)	Product, (a)×(b)	
Diester	14	---	---	---	9.5×10^4
Mineral oil	107	---	---	---	4.7×10^5
Life ratio	---	1.7	3.4	5.8	4.95

The difference in fatigue life observed with Pyroceram 9608 between diester and mineral oil lubricated tests (4.95) is reasonably close to the theoretical life ratio (5.8) established in references 6 to 8.

Reproducibility of Life Results

A wide range in rolling-contact fatigue lives of nominally identical specimens run under the same test condition is considered normal for both full-scale bearings and most bench type tests. The scatter of 20 to 1 observed in the five ball fatigue tester with AISI M-1 tool steel specimens (fig. 9) may be considered representative of bearing steels. The results for the seven Pyroceram 9608 specimen groups (figs. 7, 10, and 11) tested in this investigation all showed much lower scatter, all being within the range of 2 or 3 to 1.

A further indication of limited scatter with Pyroceram is the generation of several distinct failure spalls simultaneously. Figure 4(b) shows such a condition. Multiple spalling was observed in approximately 75 percent of the Pyroceram specimens tested. In fatigue tests of steel specimens, multiple spalling is rare if the test is terminated when the initial spall develops to running track width.

The consistent results between individual specimens and the multiple spalling of the same specimen indicate that the crystalline glass ceramic is much more homogeneous than steel. This material, having its origin as a single-phase glassy substance, is of high purity and not subject to the high-temperature reactions which produce foreign matter such as nonmetallic inclusions in bearing steels. This indicates that inclusions may be an important factor in the early failures and wide scatter encountered in bearing steels.

Fatigue life results for specimen lot B showed better life by about 2 or 3 to 1 than lot A. In the light of low scatter within each specimen group the specimen finishing may be important. Both lots were formulated, cast, and heat-treated by the same supplier. They are believed to have been processed in the same lot. The finisher of lot B (longer life) rough ground the original 3/4-inch blanks at a rate of 0.001 inch per hour and finish ground at a rate of 0.0001 inch per hour. The finisher of lot A (shorter life) did not disclose his finishing process for proprietary reasons. Although direct comparison of lots A and B on the basis of grinding rates is not possible, it is felt that effects of finishing methods such as residual grinding stresses may have a significant effect upon fatigue strength of the very hard crystallized glass ceramic material.

ANALYSIS OF RESULTS

The results of this study show that a crystallized glass ceramic does have significant rolling-contact fatigue life at moderate loads. If adequate lubrication is present, the material will fail in a manner similar to that for bearing steels. Although test temperatures were

lower than the range where ceramics may be considered as a replacement for steels, these tests indicate that the crystallized glass ceramic (Pyroceram 9608) may be useful in low-load, short-duration applications where very high operating temperature is the paramount design consideration.

SUMMARY OF RESULTS

Groups of 1/2-inch bearing balls of Pyroceram 9608 crystallized glass ceramic were run in the five ball fatigue tester. Controlled variables included ball loading (contact stress), contact angle, ambient temperature, test lubricant, and source of specimen supply. As a comparison, a group of AISI M-1 balls were run in the five ball fatigue tester under similar conditions. These tests indicate that the crystallized glass ceramic may be useful in low-load, short-duration applications where an operating temperature above the limits of steels is the paramount design consideration. Results of these tests are as follows:

1. The crystallized glass ceramic produced rolling-contact fatigue failure spalls similar to those observed with bearing steel specimens. Failures were localized in area and limited in depth of spalling.

2. The room-temperature load carrying capacity of the ceramic was found to be approximately one-fifteenth that of a group of AISI M-1 tool steel balls.

3. Fatigue life of the ceramic was found to vary inversely with approximately the 11th to 13th power of contact stress. This shows a greater sensitivity to contact stress (and load) than that of steels, which normally have an inverse 9th to 10th power relation.

4. The rate of failure spall development for Pyroceram was much slower than that for steel balls. A failed ball was intentionally overrun for a period several times that which produced the initial spalling without general track breakdown.

5. The scatter between short- and long-lived specimens was much lower for the crystallized glass ceramic (Pyroceram) than is normal for bearing steels. Since the ceramic does not have appreciable foreign matter comparable to nonmetallic inclusions in steel, this low scatter indicates that the degree of structural homogeniety may be an important factor in life scatter of bearing materials.

6. Significant differences in life between two specimen groups nominally differing only as to finisher indicate that finishing methods may have an important effect on fatigue life of the ceramic.

7. Variations in contact angle did not produce any significant differences in fatigue life of specimens run at the same contact load and Hertz stress.

8. Ambient temperature showed a significant effect on rolling-contact fatigue life. At 700° F, life was approximately one-third of that observed at room temperature. However, the material itself may not have been affected, since thermal effects on the test lubricant could theoretically produce this difference in life.

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9. The test lubricant showed a definite effect on life. The better life obtained with a paraffinic mineral oil as compared with a sebacate diester correlates well with effects of lubricant viscosity and base stock previously observed with steel balls.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, October 19, 1959

APPENDIX A

STRESS CYCLE RELATION

The following symbols are used in this appendix (see fig. 1(b)):

r radius of ball specimen and lower support balls

v_1 surface tangential velocity of test specimen at point of contact

v_2 tangential velocity of support balls

ω_1 angular velocity of drive shaft

ω_2 angular velocity of support balls around center of shaft axis

θ contact angle

The relative speed of the test specimen and the lower support balls is derived as follows:

$$v_1 = \omega_1 r_1 \qquad (r_1 = r \cos \theta)$$

$$v_1 = \omega_1 r \cos \theta$$

$$v_2 = \frac{v_1}{2} \qquad (r_2 = 2r \cos \theta)$$

$$\omega_2 = \frac{v_2}{r_2} = \frac{v_2}{2r \cos \theta}$$

$$\omega_2 = \frac{v_1}{4r \cos \theta}$$

$$\omega_2 = \frac{\omega_1 r \cos \theta}{4r \cos \theta}$$

$$\omega_2 = \frac{\omega_1}{4}$$

The relative angular speed of the upper ball to a lower ball is $\omega_1 - \omega_2 = \frac{3\omega_1}{4}$. The upper ball receives 3/4 stress cycle per revolution from each lower ball. Therefore, the number of stress cycles per revolution equals 3/4 stress cycle per ball multiplied by 4 balls, or 3 stress cycles; that is, a point on the upper ball is stressed three times per shaft revolution.

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APPENDIX B

DERIVATION OF MAXIMUM COMPRESSIVE HERTZ STRESS AS A FUNCTION OF YOUNG'S MODULUS OF ELASTICITY FOR TWO SPHERES IN CONTACT

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The following symbols are used in this derivation of maximum Hertz stress:

N_a, N_b	elastic constants
P_0	contact load
R_a, R_b	principal radii of curvature of spheres a and b
r	radius of pressure area[1]
S_{max}	maximum compressive stress
Y_a, Y_b	Young's moduli of elasticity
δ_a, δ_b	Poisson's ratio

From Hertz theory for two spheres in contact the maximum compressive stress is as follows:

$$S_{max} = \frac{3P_0}{2\pi r^2} \tag{B1}$$

Let

$$C_1 = \frac{3P_0}{2\pi} \tag{B2}$$

Then

$$S_{max} = \frac{C_1}{r^2} \tag{B3}$$

$$r = \sqrt[3]{\frac{3P_0(N_a + N_b)}{8\left(\frac{2}{R_a} + \frac{2}{R_b}\right)}} \tag{B4}$$

(See ref. 4.)

[1]For two spheres in contact the pressure area is a circle with radius r.

For two spheres of equal radii

$$R_a = R_b = R \tag{B5}$$

Then

$$r = \sqrt[3]{\frac{3P_0R(N_a + N_b)}{32}} \tag{B6}$$

where

$$N_a = \frac{4(1 - \delta_a^2)}{Y_a} \tag{B7}$$

$$N_b = \frac{4(1 - \delta_b^2)}{Y_b} \tag{B8}$$

Let

$$\delta_a = \delta_b = \delta \tag{B9}$$

Then

$$r = C_2 \sqrt[3]{\frac{Y_a + Y_b}{Y_aY_b}} \tag{B10}$$

where

$$C_2 = \sqrt[3]{\frac{3}{8} P_0R(1 - \delta^2)} \tag{B11}$$

Substituting equation (B10) into equation (B3) gives

$$S_{max} = K\left(\frac{Y_aY_b}{Y_a + Y_b}\right)^{2/3} \tag{B12}$$

where

$$K = \frac{C_1}{C_2^2} = \frac{\frac{3}{2}\frac{P_0}{\pi}}{\left[\frac{3}{8} P_0R(1 - \delta^2)\right]^{2/3}} \tag{B13}$$

$$K = \frac{3}{8\pi} \sqrt[3]{\frac{P_0}{9R^2(1 - \delta^2)^2}}$$

E-10

CA-3 back

REFERENCES

1. Bhat, G. K., and Nehrenberg, A. E.: A Study of the Metallurgical Properties that Are Necessary for Satisfactory Bearing Performance and the Development of Improved Bearing Alloys for Service up to 1000° F. TR 57-343, WADC, Nov. 1957.

2. Bisson, E. E., Johnson, R. L., and Anderson, W. J.: On Friction and Lubrication at Temperatures to 1000° F with Particular Reference to Graphite. Paper No. 57-LUB-1, ASME, 1957.

3. Stookey, S. D.: Catalyzed Crystallization of Glass in Theory and Practice. Ind. and Eng. Chem., vol. 51, no. 7, July 1959, pp. 805-808.

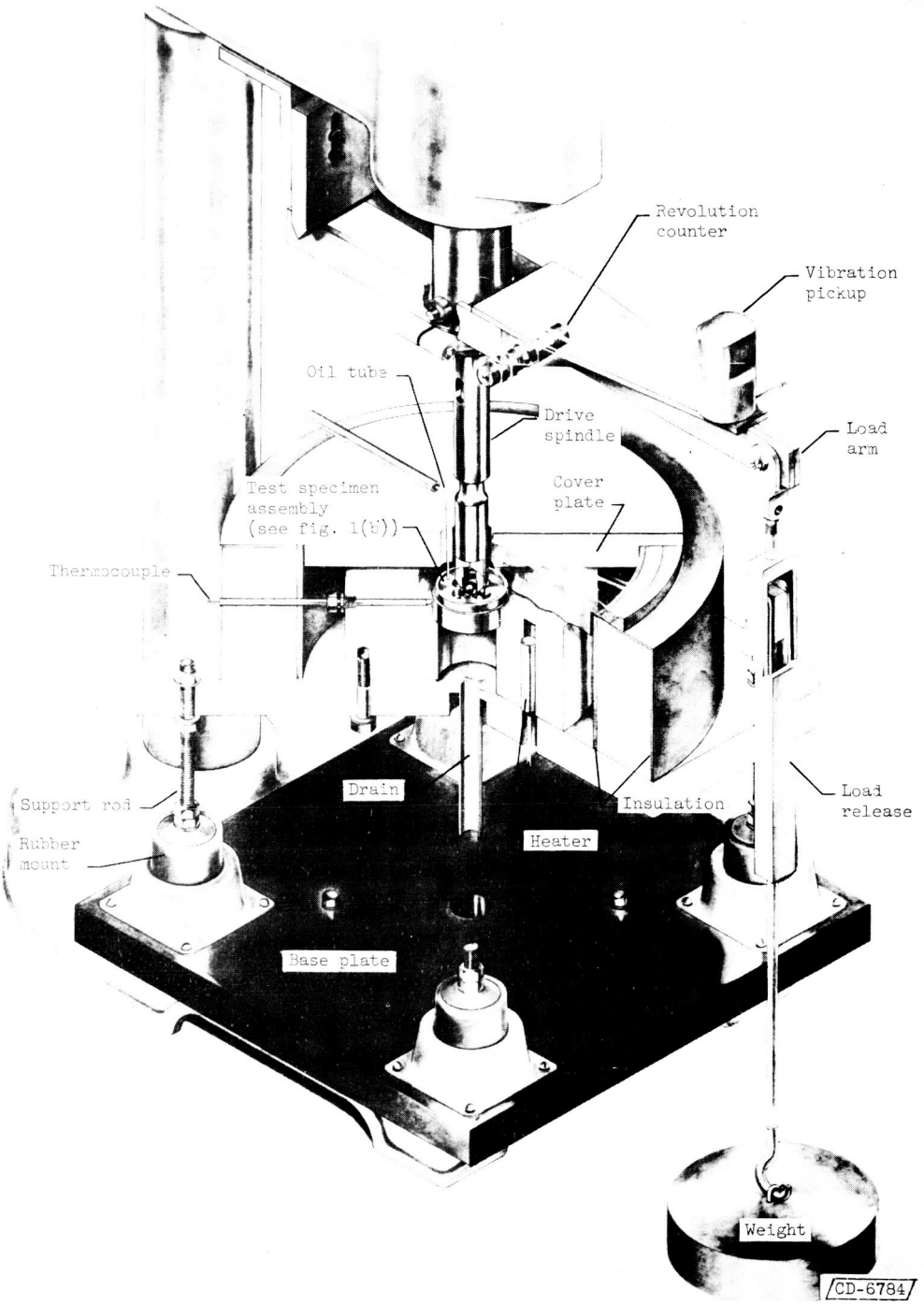
4. Jones, A. B.: New Departure - Analysis of Stresses and Deflections. Vols. I and II. New Departure, Div. Gen. Motors Corp., Bristol (Conn.), 1946.

5. Anon.: Pyroceram. Prog. Rep. PY-3, Corning Glass Works, Corning (N.Y.).

6. Carter, Thomas L.: Effect of Lubricant Viscosity on Rolling-Contact Fatigue Life. NACA TN 4101, 1957.

7. Anderson, William J., and Carter, Thomas L.: Effect of Lubricant Viscosity and Type on Ball Fatigue Life. ASLE Trans., vol. 1, no. 2, 1958, pp. 266-272.

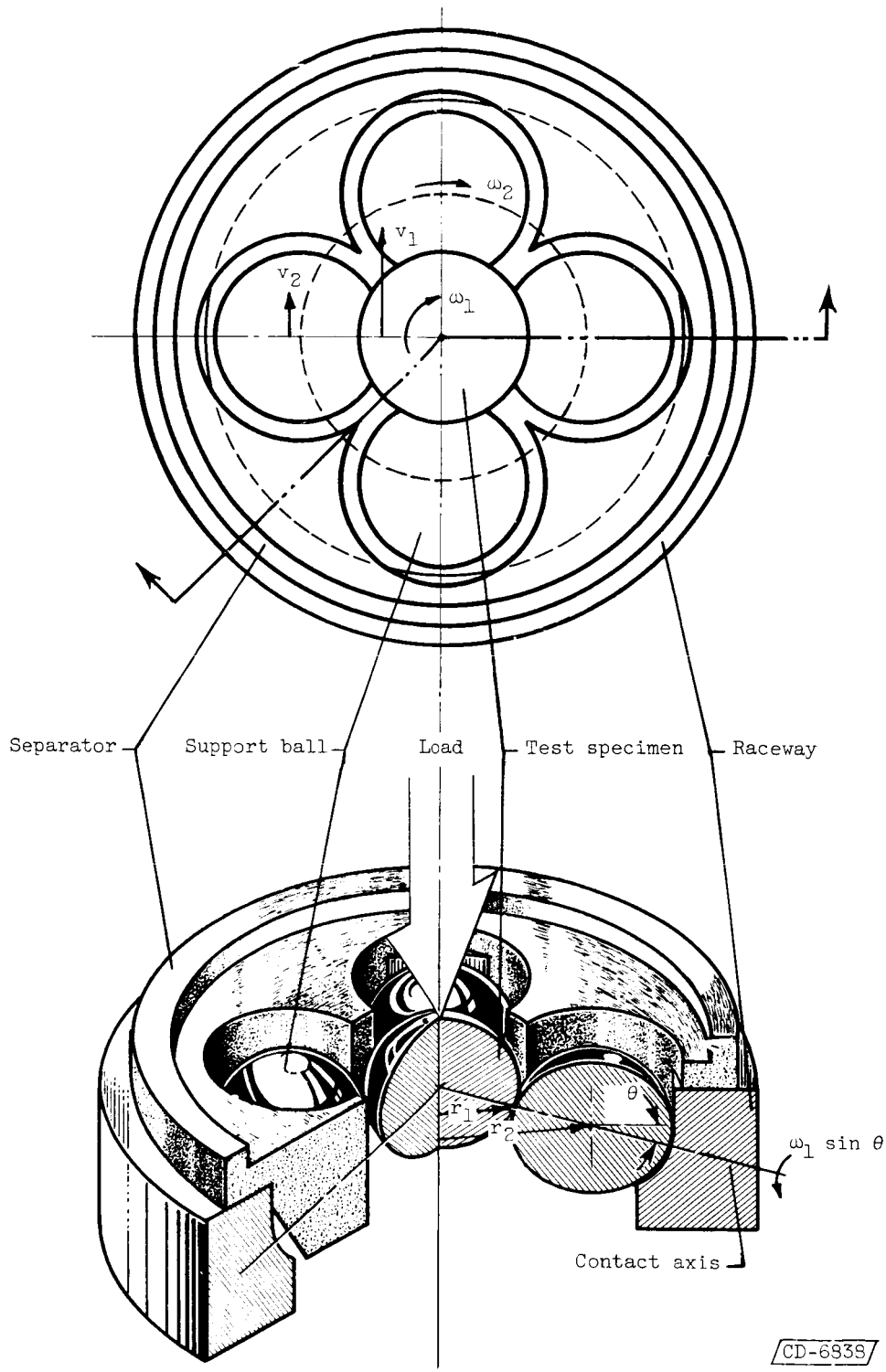
8. Carter, Thomas L.: Effect of Lubricant Base Stock on Rolling-Contact Fatigue Life. NACA TN 4161, 1958.



(a) Flexible rubber supports.

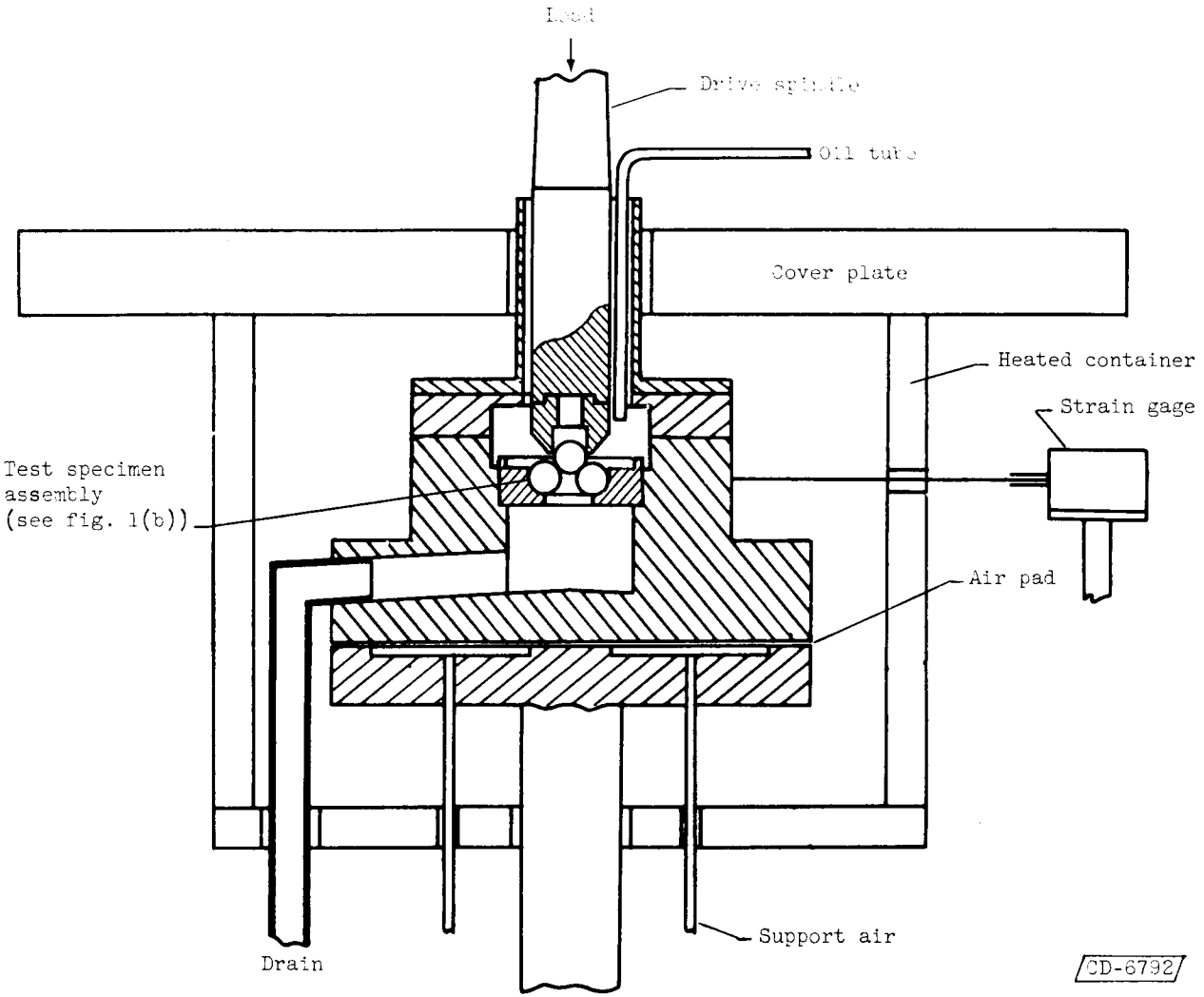
Figure 1. - Five ball fatigue tester.

E-605



(b) Schematic diagram of test section.

Figure 1. - Continued. Five ball fatigue tester.



(c) Air-bearing support.

Figure 1. - Concluded. Five ball fatigue tester.

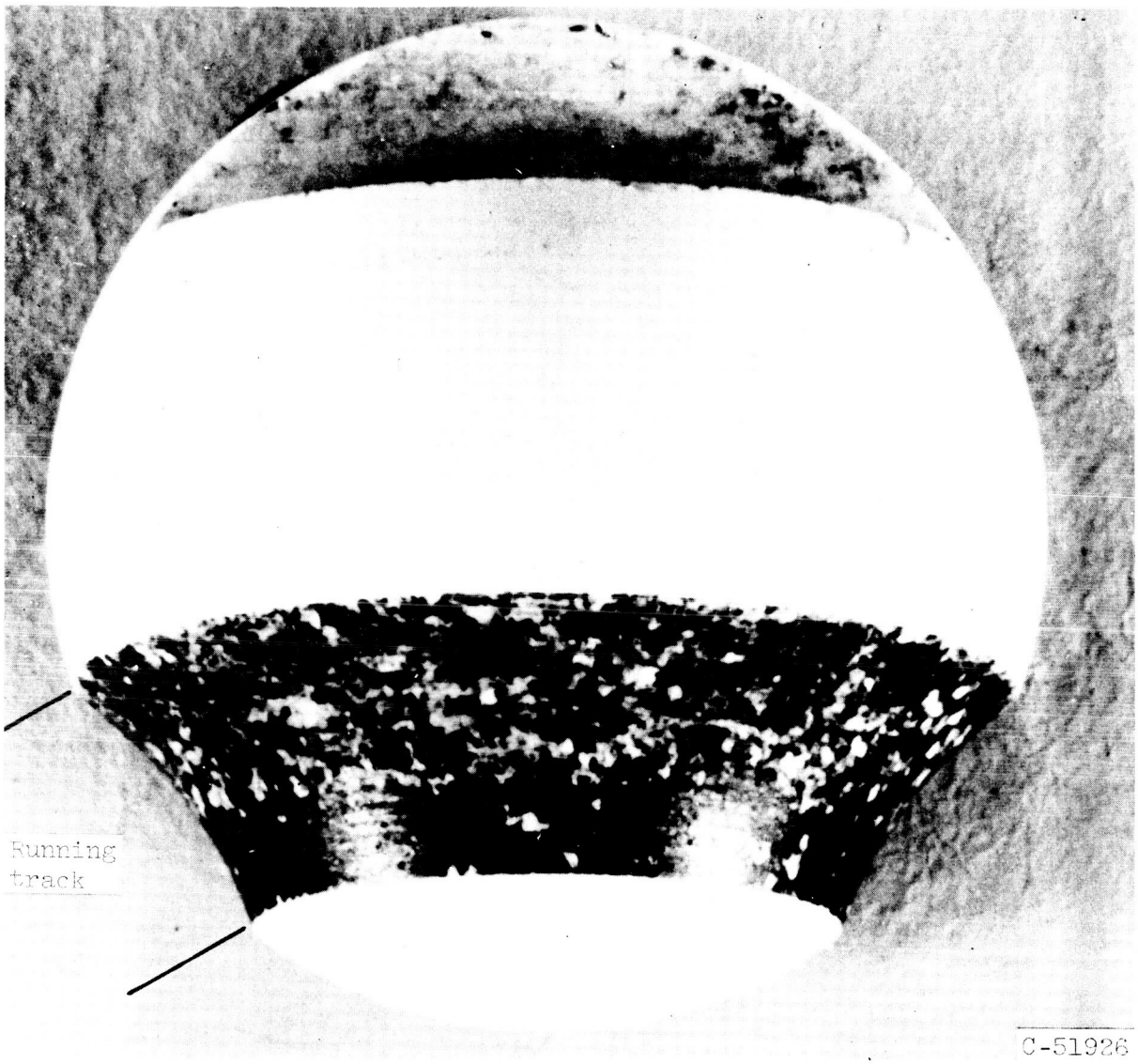


Figure 2. - Crystallized glass ceramic 1/2-inch-diameter ball specimen after 10-minute dry test. Contact load, 17 pounds (original max. contact stress, 265,000 psi); contact angle, 40°; room temperature; 70,000 stress cycles at 2430 rpm.

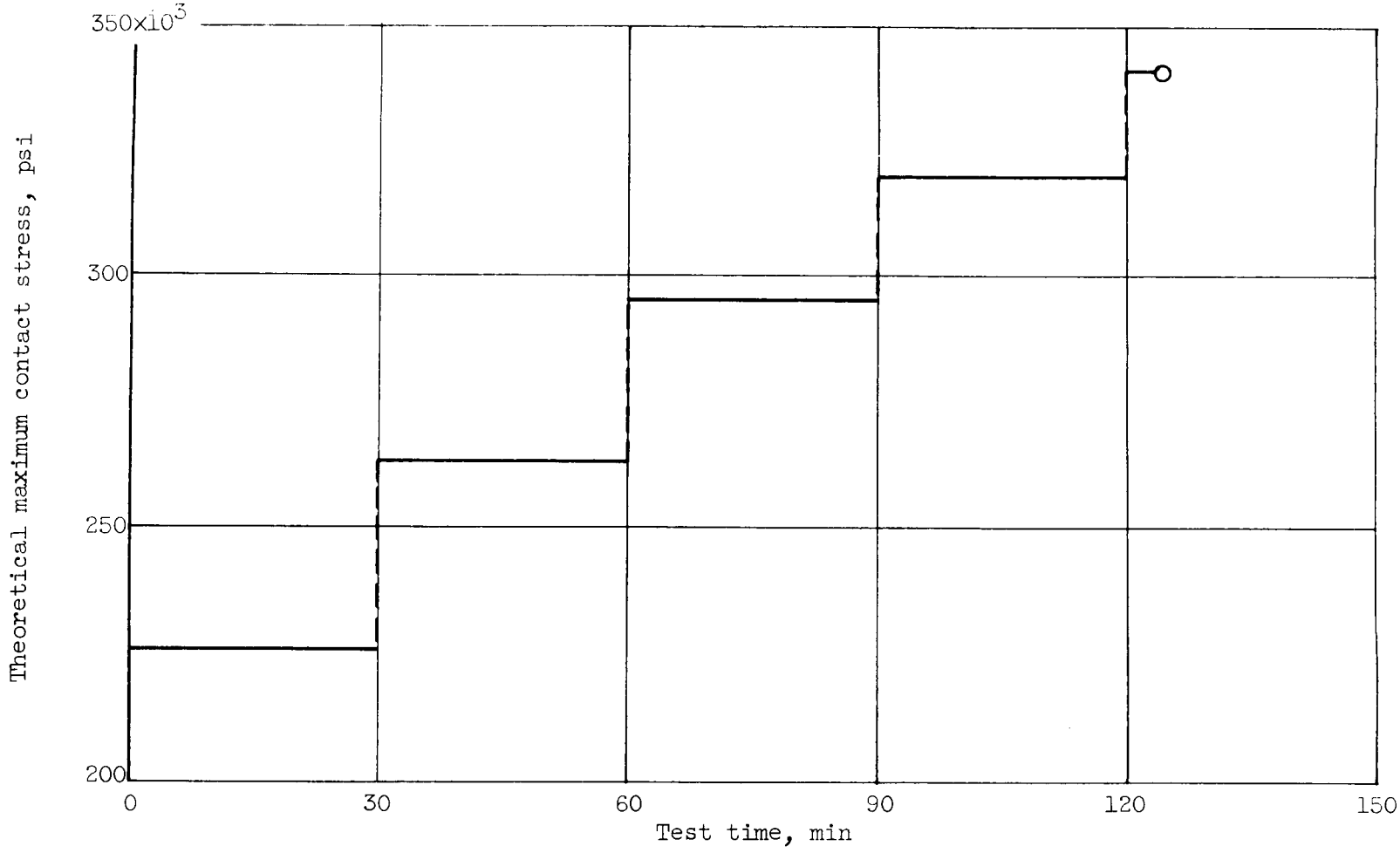


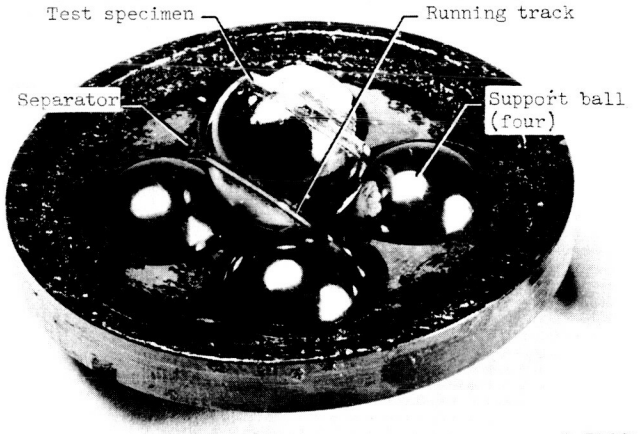
Figure 3. - Step load rolling-contact fatigue test for 1/2-inch crystallized glass ceramic ball. Contact angle, 40°; room temperature; synthetic diester lubricant; 7300 stress cycles per minute.

C-51217

(a) Before test.

C-51221

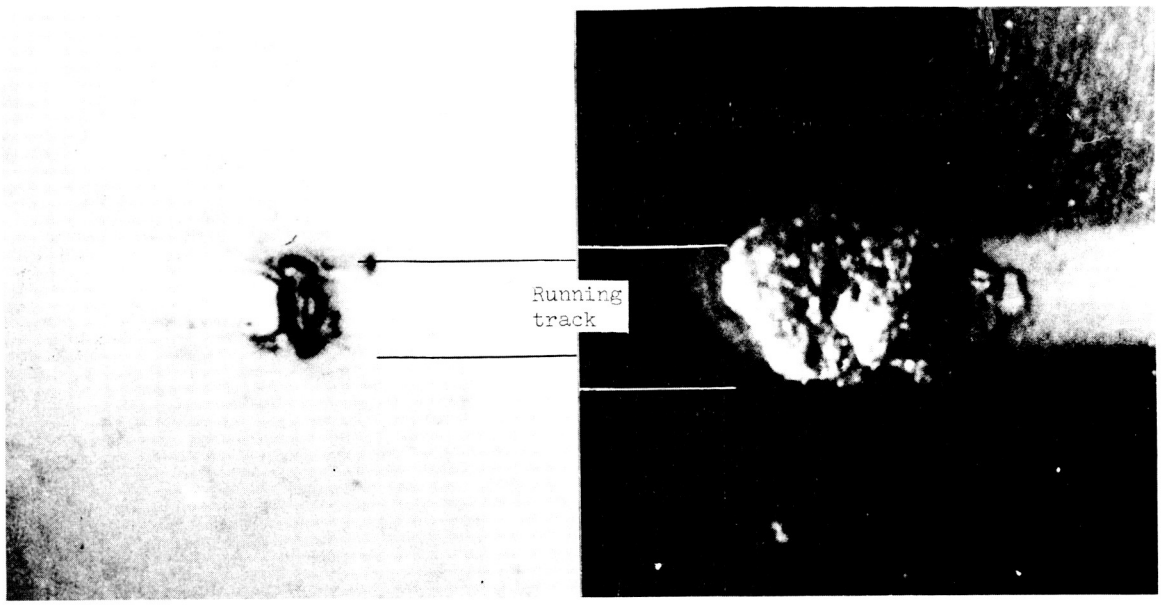
(b) After test, room temperature.



C-51024

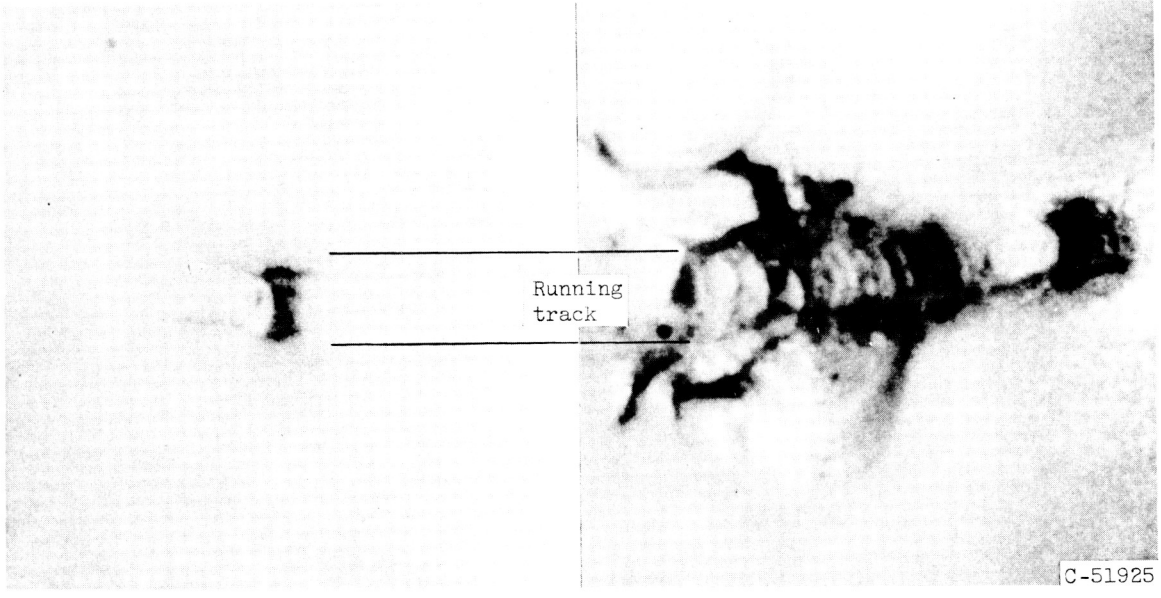
(c) After test, 700° F.

Figure 4. - Test specimens and mating parts. X1.5.



(a) Failure spall; Pyroceram 9608; 2.4×10^6 stress cycles; maximum contact stress, 265,000 psi.

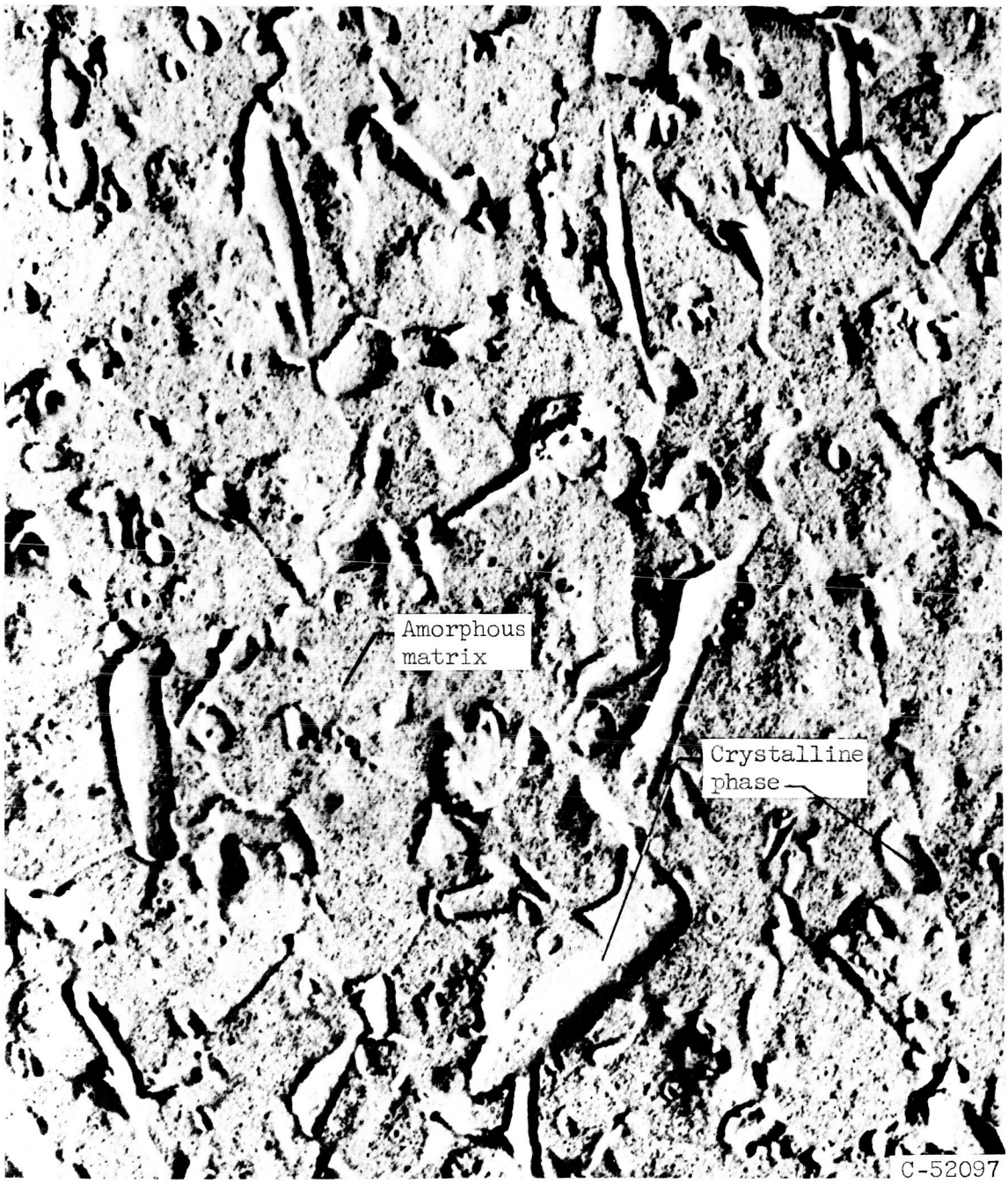
(b) Failure spall; AISI M-1; 14.5×10^6 stress cycles; maximum contact stress, 800,000 psi.



(c) Incipient failure; Pyroceram 9608; 1.8×10^6 stress cycles; maximum contact stress, 265,000 psi.

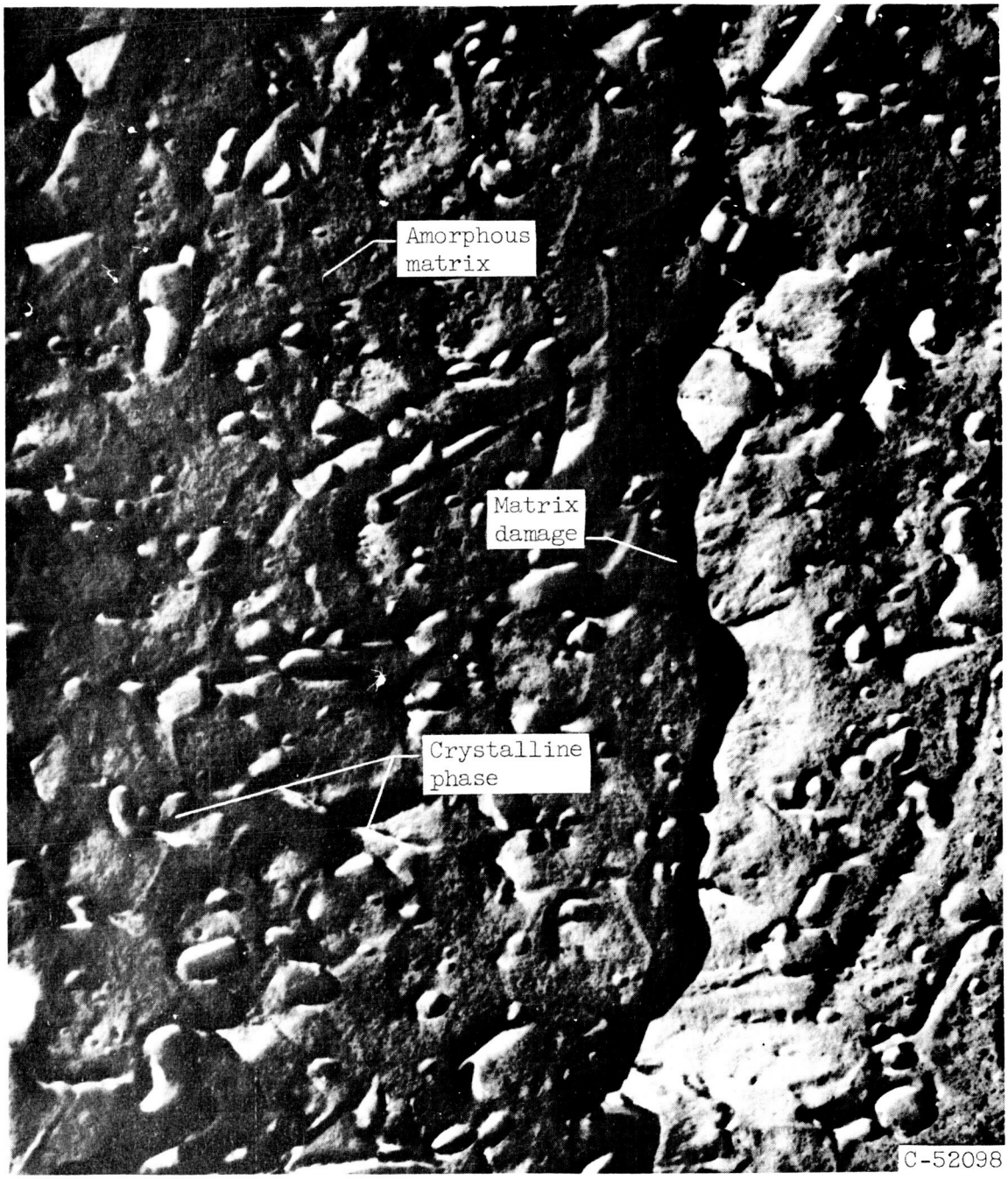
(d) Extended overrun; Pyroceram 9608; 9.2×10^6 stress cycles; maximum contact stress, 265,000 psi.

Figure 5. - Surface views of representative failure spalls with crystallized glass ceramic (Pyroceram 9608) and AISI M-1 tool steel. X30.



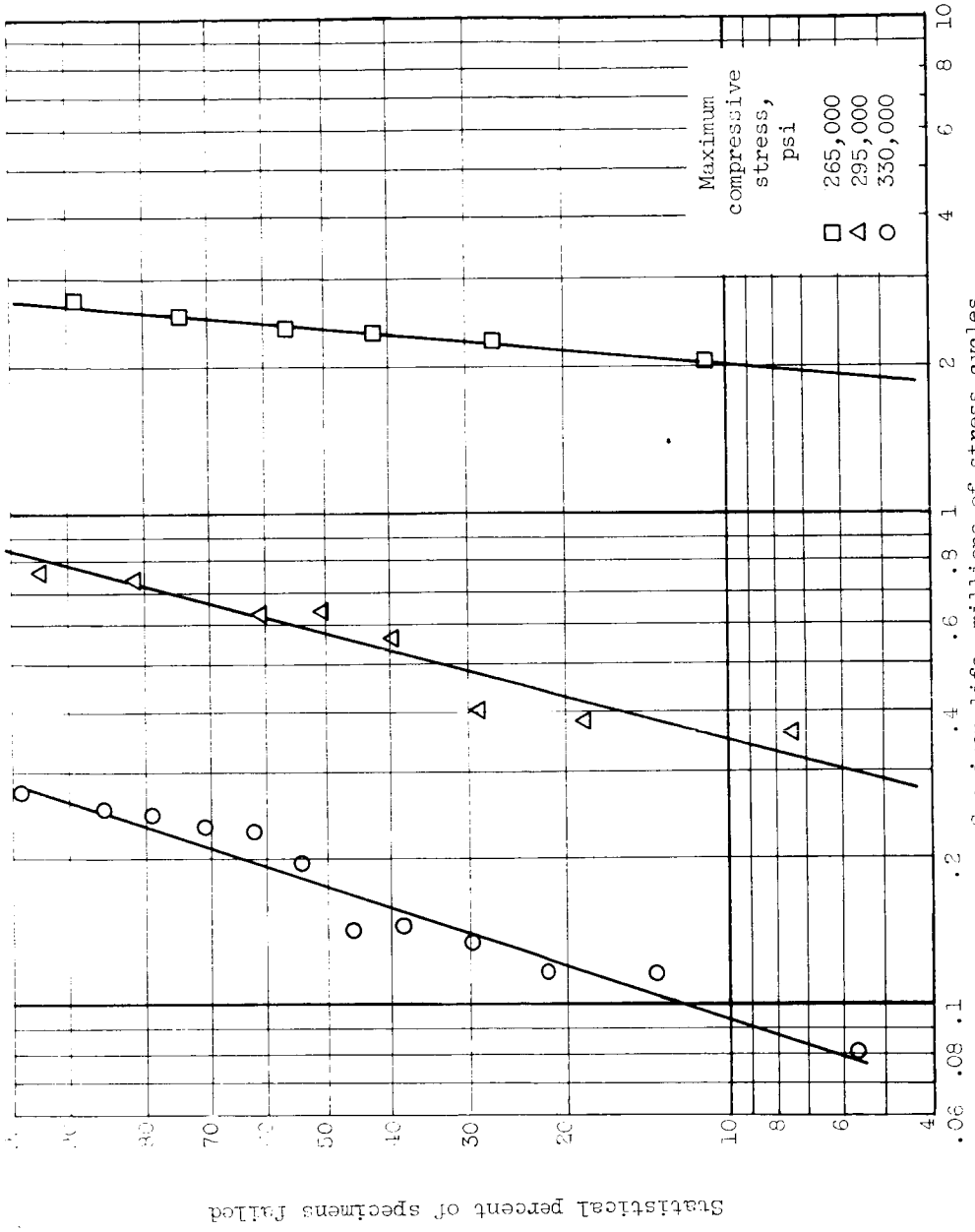
(a) Away from subsurface zone of resolved shear stress.

Figure 6. - Electron photomicrograph of crystallized glass ceramic. Fax-film replica chromium shadowed at 45°, polished with saphire abrasive on silk wheel, and etched 16 seconds in solution containing 10 percent hydrogen fluoride and 10 percent hydrogen chloride. X25,000.



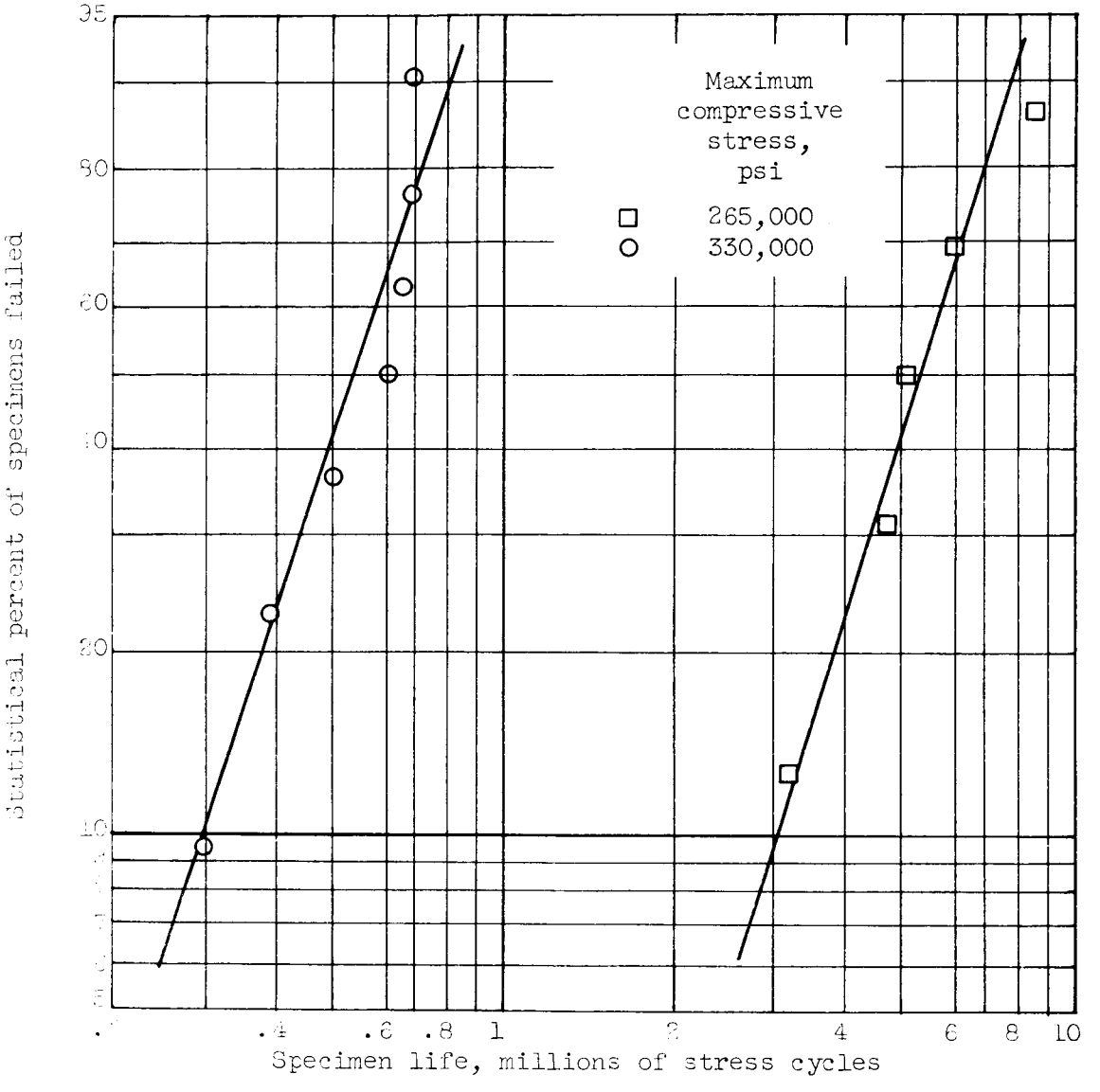
(b) In subsurface zone of resolved shear stress.

Figure 6. - Concluded. Electron photomicrograph of crystallized glass ceramic. Faxfilm replica chromium shadowed at 45°, polished with saphire abrasive on silk wheel, and etched 16 seconds in solution containing 10 percent hydrogen fluoride and 10 percent hydrogen chloride. X25,000.



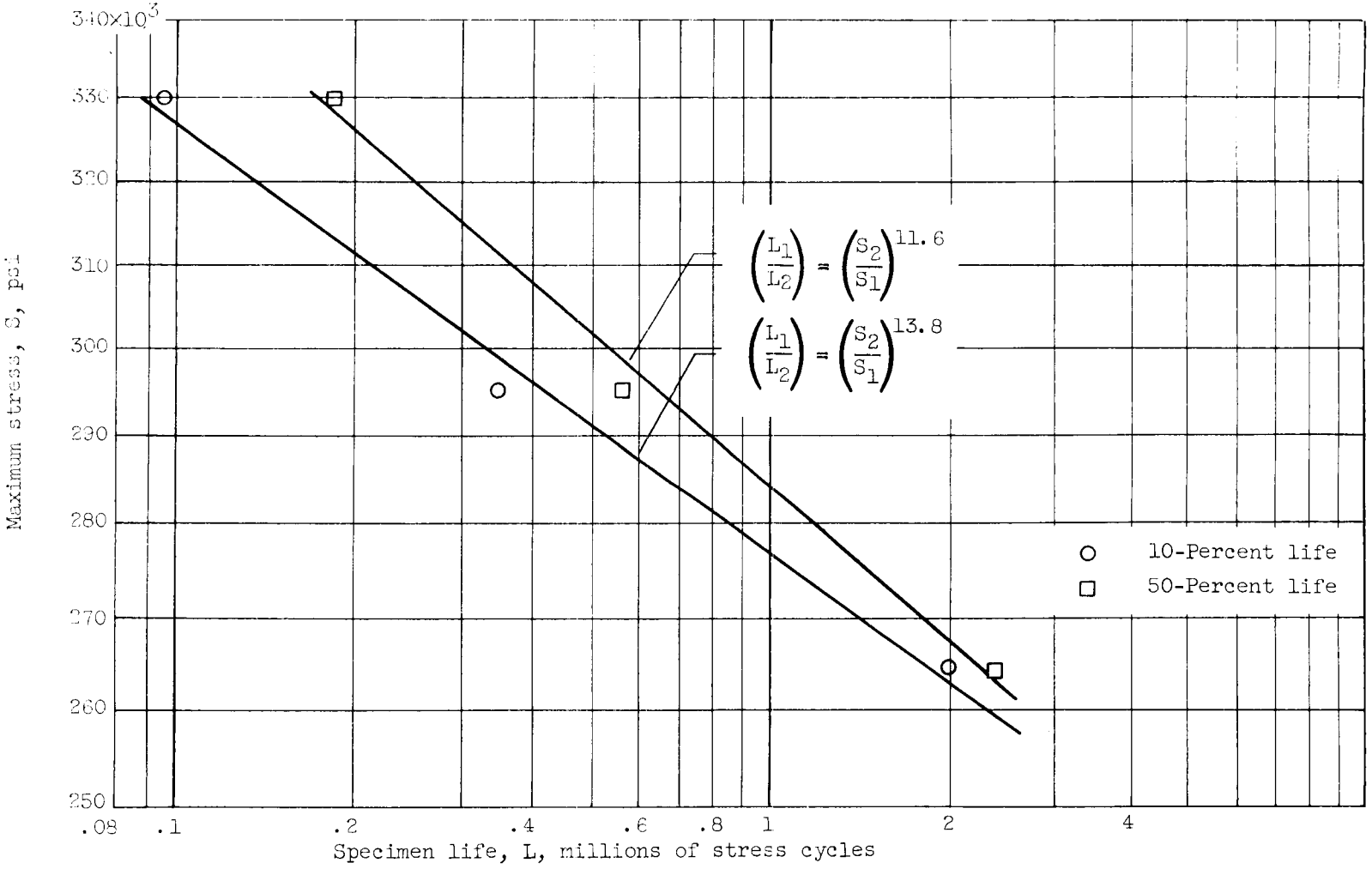
(a) Specimen lot A.

Figure 7. - Rolling-contact fatigue life of crystallized glass ceramic balls. Contact angle, 40°; room temperature; synthetic diester lubricant.



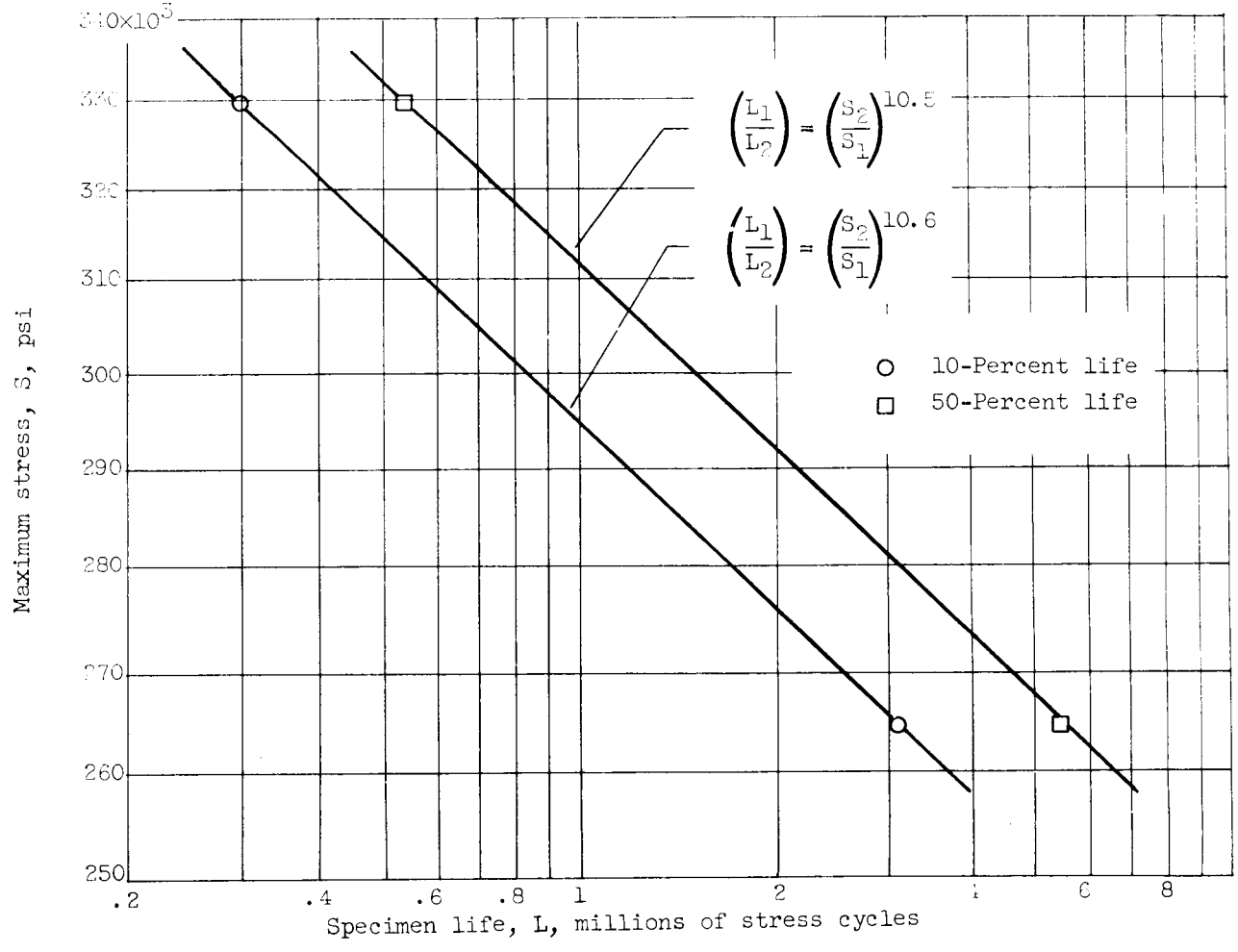
(b) Specimen lot B.

Figure 7. - Concluded. Rolling-contact fatigue life of crystallized glass ceramic balls. Contact angle, 40°; room temperature; synthetic diester lubricant.



(a) Specimen lot A.

Figure 8. - Rolling-contact fatigue life plotted against maximum theoretical compressive stress for 1/2-inch crystallized glass ceramic balls. Room temperature; synthetic diester lubricant.



(b) Specimen lot B.

Figure 8. - Concluded. Rolling-contact fatigue life plotted against maximum theoretical compressive stress for 1/2-inch crystallized glass ceramic balls. Room temperature; synthetic diester lubricant.

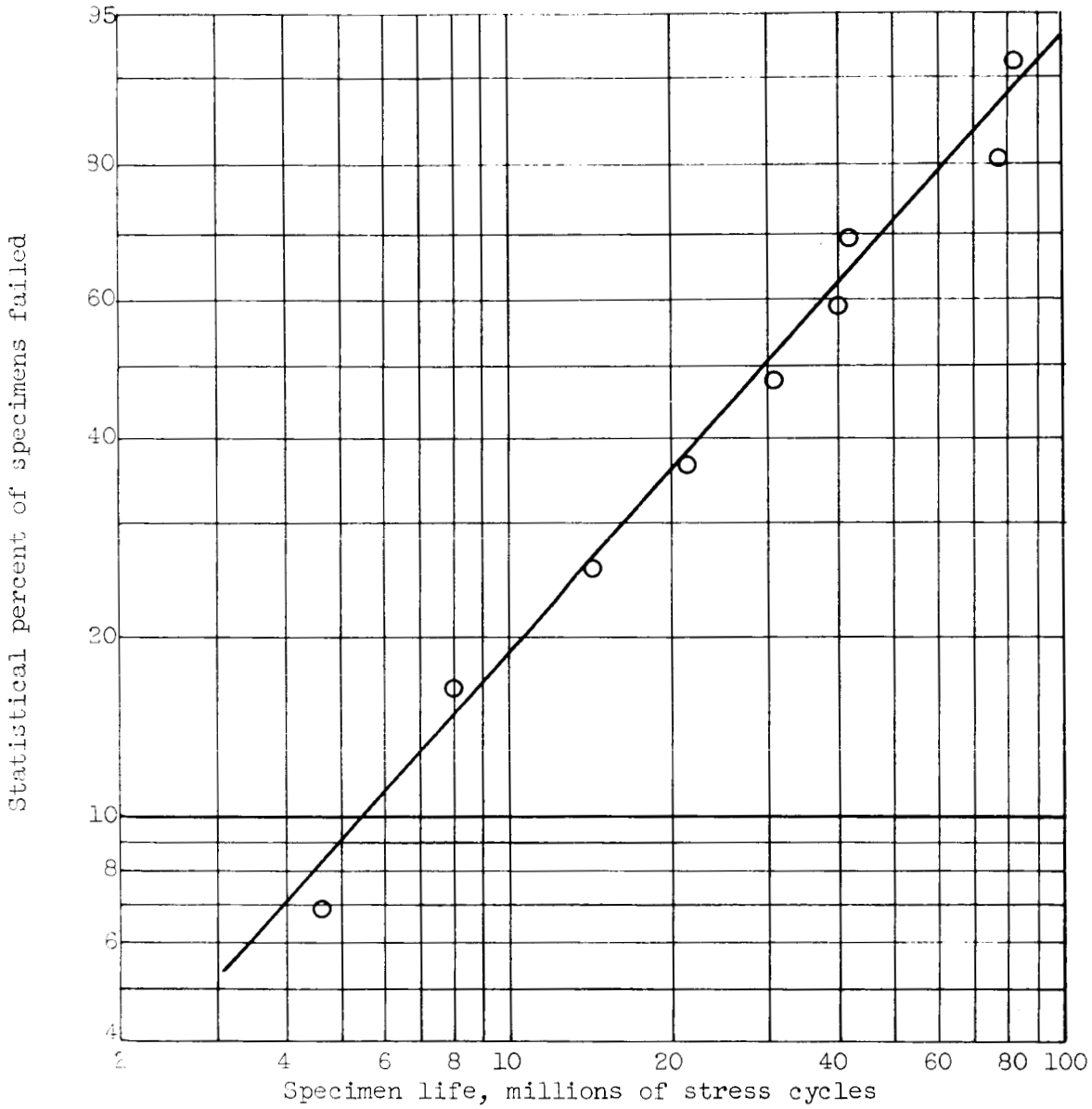


Figure 9. - Rolling-contact fatigue life of AISI M-1 tool steel balls. Contact angle, 40°; room temperature; synthetic diester lubricant; maximum compressive stress, 800,000 psi.

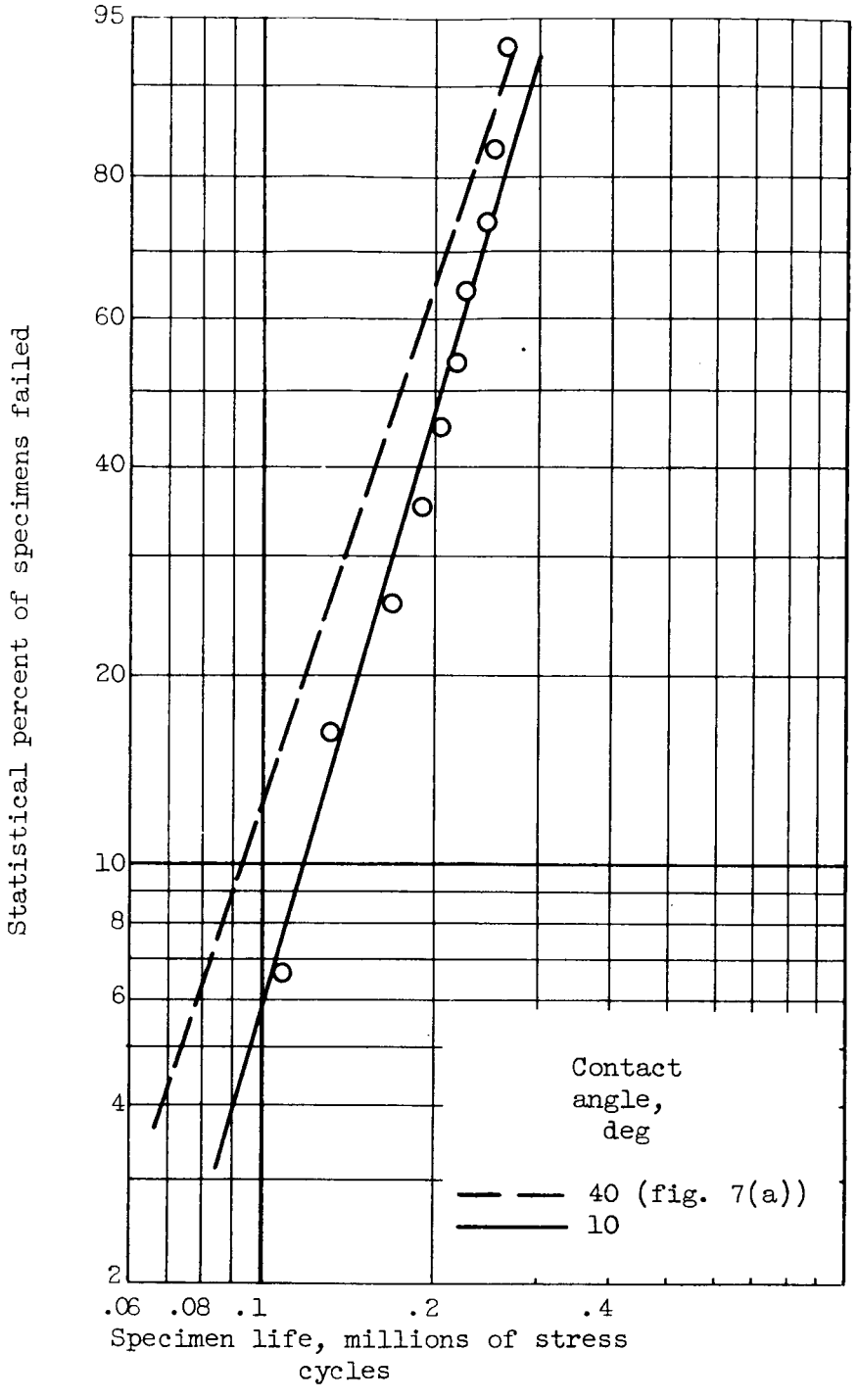


Figure 10. - Rolling-contact fatigue life of crystallized glass ceramic balls of specimen lot A as function of contact angle. Room temperature; synthetic diester lubricant; maximum compressive stress, 330,000 psi.

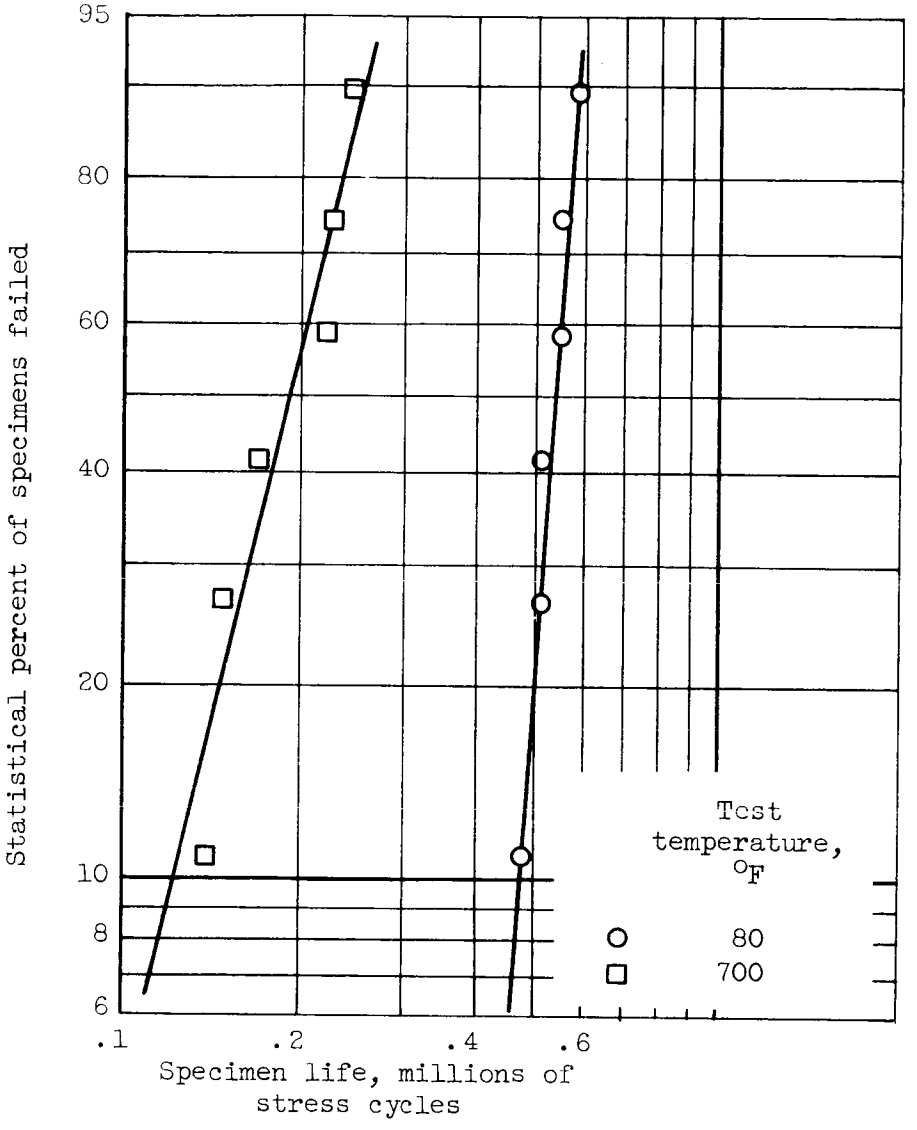


Figure 11. - Rolling-contact fatigue life of crystallized glass ceramic balls of specimen lot A as function of temperature. Contact angle, 40°; mineral oil lubricant; maximum compressive stress, 330,000 psi.